AMPLIFIER TECHNOLOGY FOR ASTROPHYSICS

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ABSTRACT

High Electron Mobility Transistors (HEMTs) play a crucial role in receivers for millimeter and sub-millimeter astrophysical observations. Low noise HEMTs are used extensively in low noise receiver front ends, for coherent direct detection and intermediate frequency (IF) amplification in heterodyne detection. Power amplifiers are becoming widely used for local oscillator (LO) subsystems in heterodyne receivers. We will describe the state-of-the-art in low noise amplifier technology stressing recent results at frequencies 1-110 GHz, with a focus on TRW's InP HEMT devices. We will describe the potential for performance improvements with a focus on proposed astrophysics applications.

INTRODUCTION

Amplifier technology plays a key role in many of the science areas specified in the Decadal report, involving the millimeter and sub-millimeter spectral regions. Scientific goals such as cosmic microwave background (CMB) polarization, high resolution spectroscopy and advanced redshift searches, all rely heavily on amplifier technology.

For CMB experiments, amplifiers have been and are currently utilized in coherent direct detection receivers in the frequency range 10-110 GHz. Cryogenic cooling of amplifiers provides receiver noise approaching 5 times quantum limited noise, approximately given by:

$$T_q=h\nu/k_B$$

In the field of high resolution spectroscopy of galactic and extragalactic astrophysical objects, low noise HEMTs provide low noise cryogenic amplification at intermediate frequencies. The first IF amplifier in the chain sets the receiver noise limit. At typical IF frequencies below 20 GHz, cooled InP HEMT devices have yielded 3 time quantum limited noise.

For receivers operating in the THz, region, local oscillator (LO) power is a problem, with traditional Gunn oscillators unable to provide adequate power to drive multipliers into the THz region. HEMT power amplifiers operating near 100 GHz, have enabled multiplier chains operating up to 1.8 THz, such as in the ESA/NASA Herschel HIFI project.

Low noise amplifiers provide another avenue of approach to high redshift surveys. Unlike mixers, low noise amplifiers are capable of very large instantaneous bandwidths. A receiver equipped with an amplifier front-end, and back-end spectral processor, can monitor fractional bandwidth of up to 50%, providing a unique tool for redshift identification. Such receivers already exist in the frequency range 20-115 GHz.

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Below we will describe the state-of-the-art in amplifier technology and applications to astrophysics. We will also describe how the technology may evolve to meet the needs of the next generation of astrophysics missions.

HEMT Devices

HEMTs are a type of Field Effect Transistor (FET), a three terminal electronic device in which a voltage applied at the gate terminal, controls the current between the other two terminals, the drain and source. With appropriate external circuitry, this can be used to produce input signal amplification. In a HEMT, the carriers are confined to a 2 dimensional electron gas, which effectively reduces scattering and increases electron mobility. HEMTs structures are produced using molecular beam epitaxy (MBE), in which molecular layers are grown in a controlled crystal lattice. A schematic cross section of an MBE grown HEMT device is shown in Figure 1.
High performance millimeter wave HEMTs must exhibit high current gain. This is enhanced at high frequencies by making the gate length as short as possible, minimizing the transit time between the drain and source. Such devices use electron beam lithography to write very small gate lengths, typically between 0.05 and 0.15 microns.

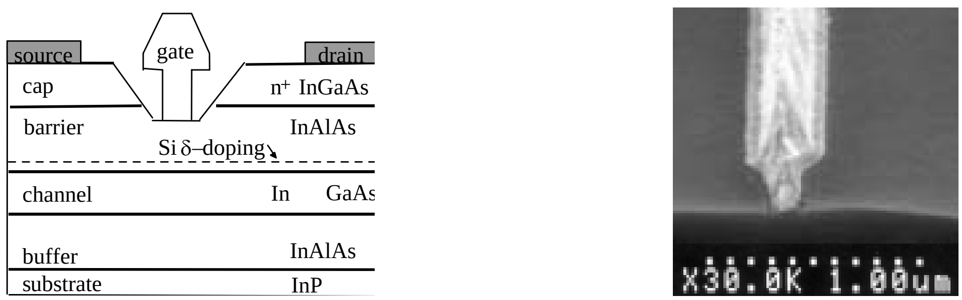

Figure 1: *The left shows a schematic cross-section of an InP HEMT device. On the right is an electron micrograph of the gate[1].*

The noise of a transistor can be characterized with an input noise, current gain and output noise. The correlation between the input and output noise of a HEMT is an ongoing area of research, but empirically, they can be treated as almost independent.[2] The gain and output noise are both dependent upon the voltage and current bias applied to the drain. For low noise applications it is desirable to have high current gain at low bias voltage and current on the drain. InP HEMTs exhibit high gain at low voltage and current and are the best low noise devices for millimeter wave applications. Cryogenic cooling of InP HEMTs typically reduces the noise by almost an order of magnitude, with increased gain, reduced current and reduced input noise. Cryogenically cooled InP HEMTs exhibit 3-6 times quantum limited noise from 4-100 GHz.

For power applications, where noise is less of a concern, it is desirable to have high gain at high voltage and current at the drain. Devices are designed to have large breakdown voltages and currents to accommodate the large signals present. In order to increase the current carrying capacity, most power amplifiers are designed with very wide (but short) gates. Power amplifiers have been built in the GHz region producing tens of watts of power. At 100 GHz, amplifiers have been produced for LO sources producing hundreds of milliwatts of power with 15% tunable bandwidth.

LOW-NOISE AMPLIFIER PERFORMANCE

The best noise results at all frequencies above 4 GHz have been obtained with InP HEMT devices. JPL and TRW have worked together on the NASA led Cryogenic HEMT Optimization Program, aimed at improving low noise performance at high frequencies. The project utilizes TRW's InP HEMT monolithic microwave integrated circuit (MMIC) process, in which the active transistor and passive circuit elements are combined in a single, fully functional amplifier chip. While trying to improve the process, CHOP also supports prototype MMIC circuit designs and amplifiers useful for ground-based radioastronomy. CHOP devices hold record performance at all frequencies from 4 to 110 GHz. The following circuits were produced under this program.

4-8 GHz MIC Low Noise Amplifier

An amplifier was built using discrete transistors, with the microwave integrated circuit (MIC) components provided by separate substrates, all connected together with wire bonds. The amplifier design was developed at Chalmers University, Sweden, using 200 micron wide CHOP devices[3]. The gain and noise figure are shown in Figure 2. These amplifiers and similar ones using the same devices are being used for IF systems on the Caltech Submillimeter Observatory, prototypes for Herschel HIFI and DSN X-band telecommunications.

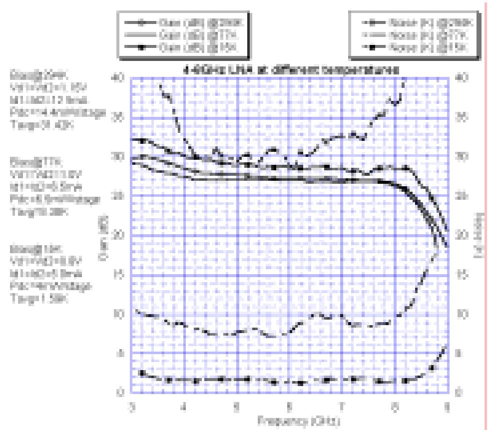

Figure 2: *The gain and noise data of the Chalmers University amplifier built with the TRW transistor. The data are shown at 295, 77 and 15 K.*

Low Noise Amplifiers from 30-80 GHz

In the frequency range 30-80 GHz, MIC amplifiers provide the best noise performance. Most of these are based upon the NRAO designs used in the MAP receivers[4]. These amplifiers, operating at 20 K using unpassivated InP devices, achieve approximately 10K noise at 30 GHz, 12K at 44 GHz and 25-30K at 60 GHz. Recent results are showing modest improvement. Jodrell Bank Observatory reports 8K noise from 27-33 GHz, using a design similar to the NRAO design, and a TRW CHOP device. Another result in this frequency range demonstrates performance similar to the NRAO design at 60 GHz, but in a MMIC amplifier.[5]

75-115 GHz MMIC Low Noise Amplifier

This MMIC amplifier, developed under CHOP, has record noise performance. The data shown in Figure 3, are from a wafer produced by TRW for the University of Massachusetts, which has developed the chips into an array receiver for the Five Colleges Radio Astronomy Observatory telescope[6]. The same chips are being used in the Planck-LFI, NASA ESE's CloudSat, several ground-based CMB experiments, the Efflesberg 100m telescope and the DSN. It is a good example of how a single, well developed design, can find applications in multiple programs.

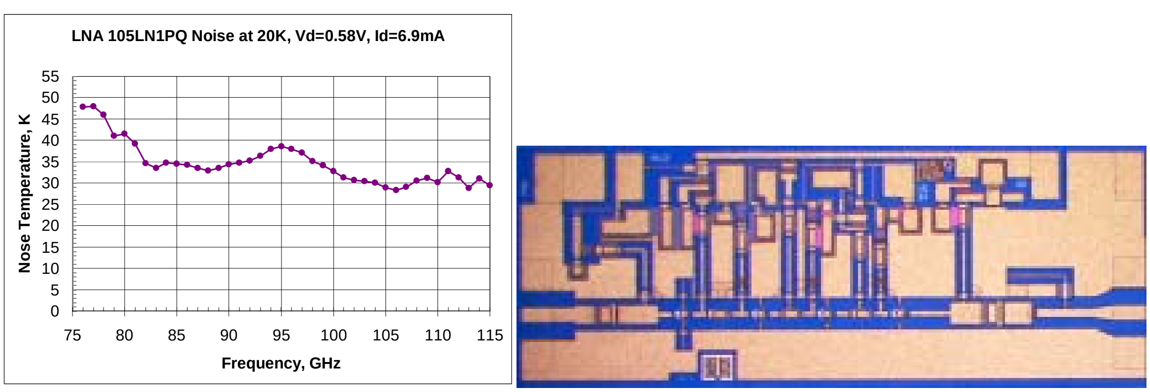

Figure 3: *Noise data at 20K are shown on the left, for the MMIC circuit pictured at the right (Data courtesy N. Erickson).*

POWER AMPLIFIERS FOR LO SOURCES

Many of the practical aspects of amplifier development are similar for low noise and power amplifiers. One major difference is the need for large area devices, capable of carrying power. This drives the circuit designers to lower impedance media, making for more challenging for designs. Nevertheless, there has been great success in the development of power amplifiers with large bandwidth.

Power Amplifiers for Herschel HIFI

Herschel HIFI had a need for power amplifiers in the 70-110 GHz range with 15% bandwidth and power output in excess of 200 mW. In addition, the amplifiers must be cooled to ~120K, which had not been demonstrated for power amplifiers prior to this program. The project chose to utilize TRW's 0.1 micron GaAs power process on 50 micron wafers. Module data showing output power for the resulting chipset is shown in Figure 4.[7] This technology development has enabled a whole new class of instruments for space science, Earth science and planetary exploration.

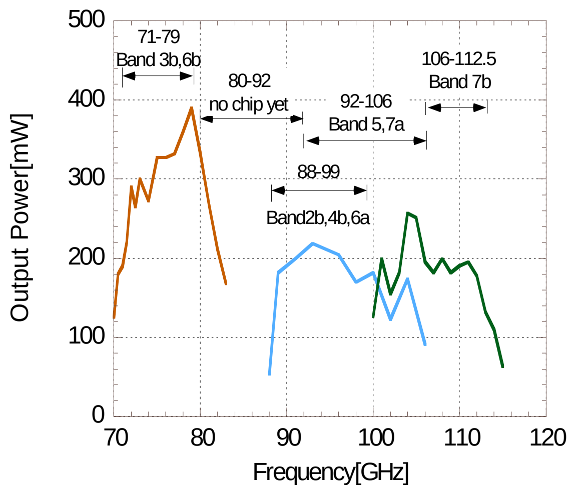

Figure 4: *The output power of the power amplifier chipset developed for Herschel HIFI.*

InP Power Amplifiers

As with low noise amplifiers, InP offers performance advantages over GaAs, for power applications. In particular, the increased current gain allows for higher frequency amplifiers with broader bandwidth. Amplifiers have been designed and built with 1.5 octaves of bandwidth up to 160 GHz. These amplifiers are capable of generating between 10 and 30 mW across the band. A description of this technology is given in Samoska et.al. in these proceedings.[8]

MULTIFUNCTION INTEGRATION

One of the advantages of amplifier technology is being able to combine the gain function of an amplifier with other required functions of a receiver.[9] Using MMIC technology the integration is made less complicated, requiring only interconnecting substrates, bond ribbons or wires and a stable package design. Higher level integration is also possible by integration of multiple functions on a single chip, such as amplifiers and mixers or amplifiers and frequency multipliers.

Figure 5 shows a 100 GHz Planck-LFI Front-End-Module, which combines most of the functionality of a pseudocorrelation receiver, in a single compact package. The package has two parallel low noise amplifier chains, followed by an InP PIN phase switch. The waveguide input and output are custom flanged, to mate with a pair of compact magic-tee hybrid couplers, which complete the functionality. The receiver noise is measured to be 49K and the isolation is greater than 20 dB across a 30 GHz bandwidth, far greater than was achievable with discrete components.

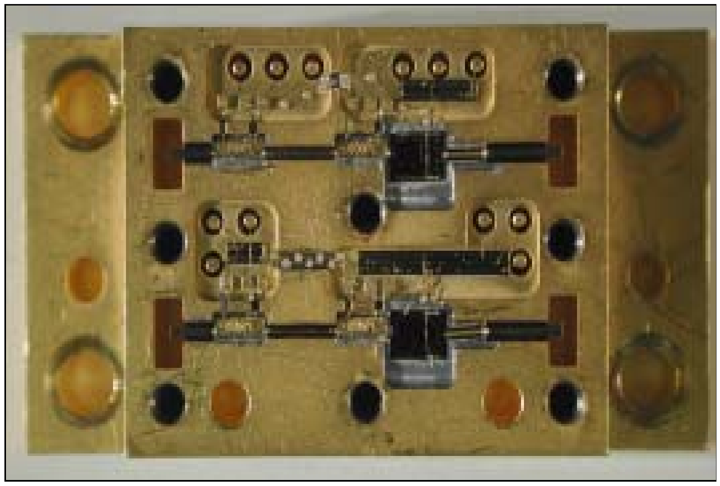

Figure 5: *A photograph of the interior of the Planck-LFI 100 GHz front-end module, fabricated by TRW. From the left is the WR-10 waveguide input, two MMIC low noise amplifiers a phase switch and output waveguide, all in a parallel pair.*

Custom chipsets are being developed for a variety of millimeter and sub-millimeter applications[8]. At the same time, multi-use utility chips are also being developed, which serve as the building blocks for the next generation of receivers. The data from one such chip are shown in Figure 6. The chip, produced on the CHOP program, demonstrates 20 dB gain from 1-110 GHz.

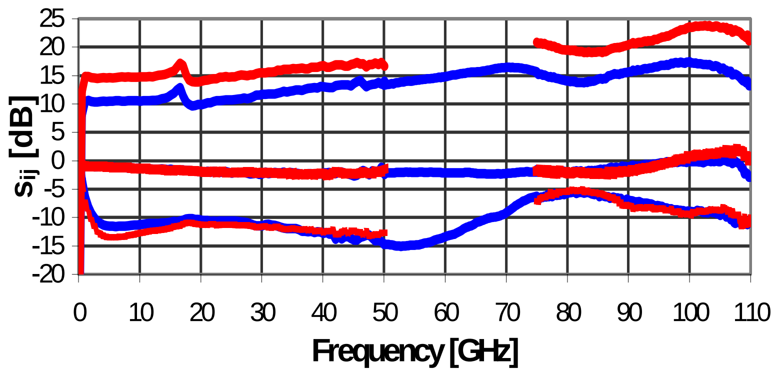

Figure 6: *Gain and return loss data as measured by wafer probe of a 1-110 GHz MMIC. The enormous instantaneous bandwidth achieved in this chip is likely to have broad applications in instrumentation.*

FUTURE DIRECTIONS

Long-term science goals for astrophysics will require aggressive technology development in device performance, circuit design as well as packaging technology.

Broadband spectral search engines are enabled by both the low noise amplifier front-ends and the multi-octave bandwidth back-end chips. The 1-110 GHz chip described earlier, is a key building block of a 100 GHz bandwidth spectrometer.

A CMB polarization mission will require frequency coverage from 30-650 GHz in order to remove polarized foregrounds. The sensitivity of an experiment capable of detecting B-mode polarization must be an order of magnitude better than Planck-LFI. At frequencies below 100 GHz, cryogenic low-noise amplifiers offer the best chance of achieving this goal. MMIC processes allow for massive arrays to be manufactured, integrating full radiometer functionality in a compact front-end package. Prototypes of such receivers should be developed in the next few years. Automated assembly techniques, already employed in the semiconductor industry, allow for thousands of integrated modules to be fabricated at modest cost.

Coherent detection offers an advantage over bolometers for polarization measurement, namely simultaneous measurement of the Q and U Stokes parameters. Once the signal is amplified and the penalty is paid for noise, multiple functions can be performed on the signals, allowing simultaneous measurement of multiple parameters. This effectively halves the number of feed horns required in the focal assembly. If the optical design can be arranged, an array of 1000 compact HEMT receivers using Q/U detection, offers an order of magnitude improvement in sensitivity over LFI.
Finally, it is expected that devices will continue to improve over the next decade. While InP represented a great performance improvement over GaAs, InP continues to improve. At 100 GHz in 1995 the best narrow band result was 50 K. Today we have seen 30K at 106 GHz. There is still room to maneuver in the InP material system and one can anticipate some improvement. With 3x quantum limited noise already demonstrated at 8 GHz, we might expect 15-20 K performance from InP HEMTs at 100 GHz.
Just as InP provided revolutionary performance over GaAs, new material systems are being explored. DARPA has recently funded an Antimonide Based Compound Semiconductor technology development program, similar to the program that led to InP. Physics based models of the materials predict high current gain at even lower voltage and current than InP (roughly half). This translates to an even greater reduction in noise, making 15K or 3x quantum limited noise at 100 GHz a good possibility. TRW is leading a team of developers, including JPL, in this effort. If Sb HEMTs follow the same development path as InP, state-of-the-art devices will be obtained in one or two years, with MMIC circuits coming soon after. With close cooperation between receiver developers and device technologists, cryogenic receivers are possible within a few years. A factor of two improvement in noise performance reduces the size of a polarimeter array by a factor of four. All things considered, an order of magnitude improvement over LFI is therefore well within reach in the next decade.

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